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# ASCA Observation of MS 1603.6+2600 (=UW Coronae Borealis): a Dipping Low-Mass X-ray Binary in the Outer Halo?

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## ABSTRACT

MS 1603.6+2600 is a high-latitude X-ray binary with a 111 min orbital period, thought to be either an unusual cataclysmic variable or an unusual low-mass X-ray binary. In an *ASCA* observation in 1997 August, we find a burst, whose light curve suggests a Type I (thermonuclear flash) origin. We also find an orbital X-ray modulation in MS 1603.6+2600, which is likely to be periodic dips, presumably due to azimuthal structure in the accretion disk. Both are consistent with this system being a normal low-mass X-ray binary harboring a neutron star, but at a great distance. We tentatively suggest that MS 1603.6+2600 is located in the outer halo of the Milky Way, perhaps associated with the globular cluster Palomar 14, 11° away from MS 1603.6+2600 on the sky at an estimated distance of 73.8 kpc.

*Subject headings:* X-rays: stars — stars: individual (MS 1603.6+2600=UW CrB)

## 1. Introduction

MS 1603.6+2600 was first discovered in the course of the Extended Medium Sensitivity Survey (Gioia et al 1990). With only 51 detected photons in a 2112 s exposure, this detection was useful

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only in providing the position and a flux estimate of $\sim 10^{-12}$ $\mathrm{ergs\,cm^{-2}\,s^{-1}}$ (0.3–3.5 keV). Morris et al (1990) identified the optical counterpart, subsequently designated UW Coronae Borealis, a V $\sim$19.7th mag object. It was shown to be an eclipsing binary: measurements of 10 eclipse timings over a 3-day period has enabled Morris et al (1990) to derive a 111.0 min orbital period. This immediately establishes MS 1603.6+2600 as a low-mass, compact binary. To fit in such a short period binary, the secondary must be a low mass star; and, to be a significant X-ray source, the primary must be an accreting compact object — a white dwarf, which would make the system a cataclysmic variable (CV), a neutron star, or perhaps a black hole, either of which would make it a low mass X-ray binary (LMXB). Given the high galactic latitude of this object ($b^{\mathrm{II}} \sim 47°$), it has to be at a large distance ($d \gg 10$ kpc) to be a normal, bright LMXB. On the other hand, the optical spectrum and the high X-ray to optical flux ratio ($f_X/f_{opt} \sim 15$) are unlike those of normal CVs.

Further optical observations (Vilhu et al 1993; Hakala et al 1998) have revealed highly variable orbital light curves. Report of a 112.5 min period, obtained by Vilhu et al (1993) from Fourier analysis, would make it a system with multiple periods, if confirmed. A *ROSAT* PSPC observation performed on 1991 August 26 (Hakala et al 1998) did not resolve the nature of MS 1603.6+2600. Hakala et al (1998) discussed the possibility that MS 1603.6+2600 may be an LMXB with an accretion disk corona (ADC), in which we only observe a small fraction of X-rays scattered in the ADC surrounding the inner disk and the neutron star. They also considered the possibility that it might be a transient LMXB in quiescence. These scenarios are motivated, in part, by the desire to keep MS 1603.6+2600 within a few kiloparsecs of the Galactic plane.

We have obtained an *ASCA* observation of MS 1603.6+2600 in an effort to clarify the nature of this object (see also our preliminary report in Mukai et al (1999)). We describe the observation in §2, the results in §3, and discuss the implications in §4.

## 2. Observation

MS 1603.6+2600 was observed with *ASCA* (Tanaka et al 1994) from 1997 August 30 at 20:25 UT to 1997 August 31 at 13:52 UT. Of the 4 instruments on-board *ASCA*, the 2 GIS's were operated in the standard PH mode. For the GIS data, we have selected intervals when the satellite was outside the South Atlantic Anomaly (SAA), the attitude control was stable and within 0.02° of the target, and the line-of-sight was $> 5°$ above the Earth limb. We have also applied a standard selection expression combining monitor count rates and geomagnetic cut-off rigidity (COR) to exclude time intervals of high particle background, obtaining $\sim$25 ksec of good on-source data. We extracted the source spectra and light curves using 6 arcmin radius circular extraction regions, and used $\sim$13 arcmin radius regions around the center of the detectors, excluding regions within $\sim$7.5 arcmin of the source, as background (no sources were detected in the background regions both for GIS and for SIS). The net count rates were $\sim$0.06 $\mathrm{cts\,s^{-1}}$ in GIS-2 and $\sim$0.07 $\mathrm{cts\,s^{-1}}$ in GIS-3.

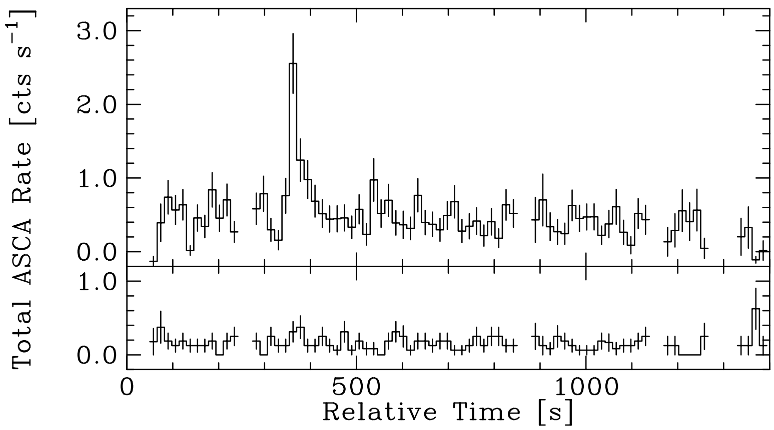


Fig. 1.— (Upper panel) *ASCA* light curve of the burst, in 16 s bins. We show the total count rate for 2 SIS (0.48–10 keV) and 2 GIS (0.7–10 keV) instruments. (Lower panel) The background light curve during the same interval.

For the 2 SIS instruments, we have applied the same SAA, attitude, and elevation constraints, and further excluded data taken within 10° of the bright Earth limb. We have selected low background time intervals using COR and PIXEL monitor count criteria, and also excluded data taken within 32 seconds of day/night and SAA transitions, when the on-board dark frame calculations are suspect. These resulted in ∼25 ksec of useful SIS data. We used an extraction region of ∼4.5 arcmin radius for the SIS-0, using the entire chip, excluding regions within ∼5.5 arcmin of the source, as background, with a net rate of ∼0.12 cts s$^{-1}$. For SIS-1, we were forced to use a smaller (∼3.5 arcmin) source region to stay entirely within the active chip, obtaining a net rate of ∼0.08 cts s$^{-1}$.

For spectral analysis, we combined data from like instruments to form a GIS spectrum and an SIS spectrum. The latter is affected by the secular change in SIS performance at low energies; this can be phenomenologically characterized as a spurious excess absorption of order $N_H = 1.0 \times 10^{21}$ cm$^{-2}$. For the light curve analysis, we combined data from all 4 instruments, both using the entire *ASCA* passband, and in two sub-bands, one below 2 keV (0.48–2.0 for SIS and 0.7–2.0 keV for GIS) and the other above 2 keV (up to 10 keV).

## 3. Results

### 3.1. Detection of a burst

We present a 16-s bin light curve of a striking, flare-like event in Figure 1. This event, detected at 21:45:50 UT on 1997 August 30, is seen in all 4 individual source light curves, and in none of

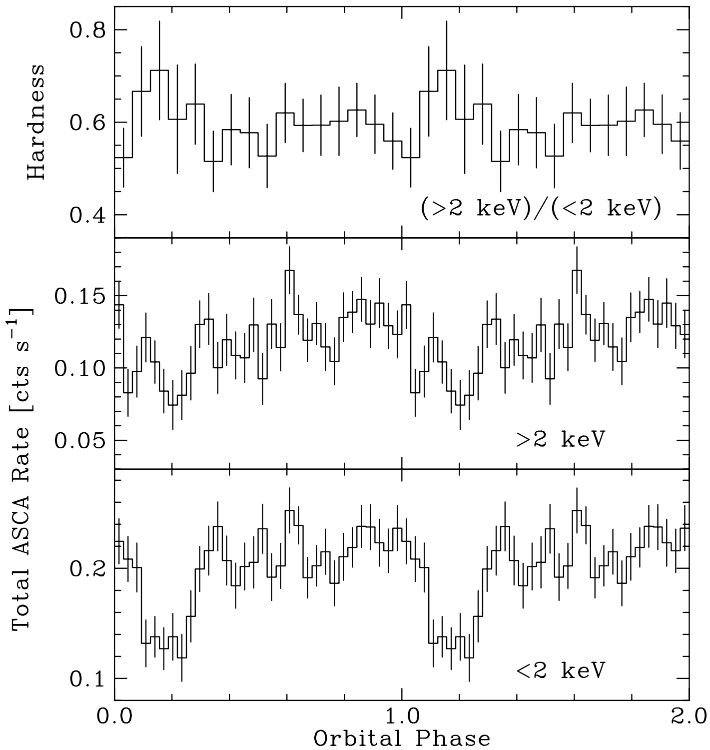


Fig. 2.— The *ASCA* light curves of MS 1603.6+2600 above and below 2 keV, folded on the orbital ephemeris of Morris et al (1990), in 32 bins per cycle, plotted twice for clarity. A hardness ratio plot is shown on the top panel in 16 bins per cycle.

the 4 background light curves. We are therefore confident that this is a real event, presumably due to MS 1603.6+2600. The rise is rapid, and the decay lasts for about 1 minute before blending into the (noisy) persistent emission. The peak count rate ($\sim 2.6$ cts s$^{-1}$ in 4 detectors) is 8 times the persistent emission.

We have attempted a more detailed analysis of this event, but this has not been fruitful because there are only ∼60 net counts from this event. In the remainder of this paper, we will refer to this event as a "burst." The resemblance with a Type I X-ray burst (i.e., a thermonuclear runaway on the surface of an accreting neutron star; see Lewin et al (1995) for a review) is suggestive, but not conclusive.

### 3.2. Orbital modulation

Next, we removed the burst from our light curves and performed Fourier and folding analyses. We find a strong periodicity at 116±6 min, the large uncertainty being due to the limited duration

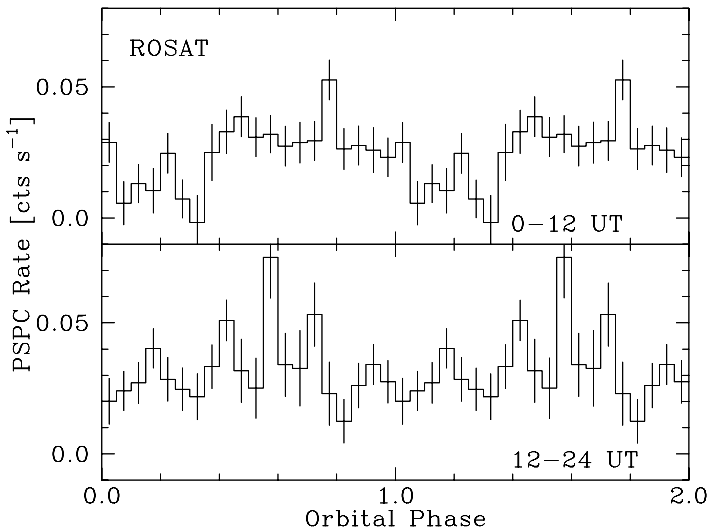


Fig. 3.— The archival *ROSAT* PSPC light curve of MS 1603.6+2600, obtained on 1991 August 26. The data have been divided into two sections, and folded on the orbital period with 20 bins.

of the observation and data gaps. We interpret this signal as reflecting the orbital modulation, and proceed below by folding the data on the orbital ephemeris of Morris et al (1990). Note, however, that this ephemeris does not define phase 0.0 accurately. No other periodicities are apparent in the data in the 200–20,000 s range.

We present the folded orbital light curves, in high (>2 keV) and low (<2 keV) energy bands, as well as the hardness ratio, in Figure 2. A clear orbital minimum, lasting ∼15% of the orbit and reaching ∼60% of the flux level outside the minimum, is seen in the low energy light curve. It is less clear in the high energy curve, which is reflected in the slight increase in the hardness ratio at these phase intervals. Inspection of individual orbital cycles shows that the minimum is always present during the same phase in broad outline, though their details vary. However, given the statistics, we cannot rule out statistical fluctuation as the cause of the cycle-to-cycle variations. Outside the minimum, the light curves are flat, with apparently random fluctuations superimposed.

This behavior is rather different from that reported by Hakala et al (1998) in their 1991 *ROSAT* PSPC observation. To investigate this further, we have retrieved the *ROSAT* data from the HEASARC and re-extracted the light curves. At first glance, we merely confirmed the results of Hakala et al (1998). However, after dividing the *ROSAT* data into two halves of roughly equal durations (∼12 hrs), we find a pattern of orbital minimum for the first half of the *ROSAT* observation (Figure 3). This minimum is absent during the second half; instead, the folded light curve shows a flaring-like behavior.

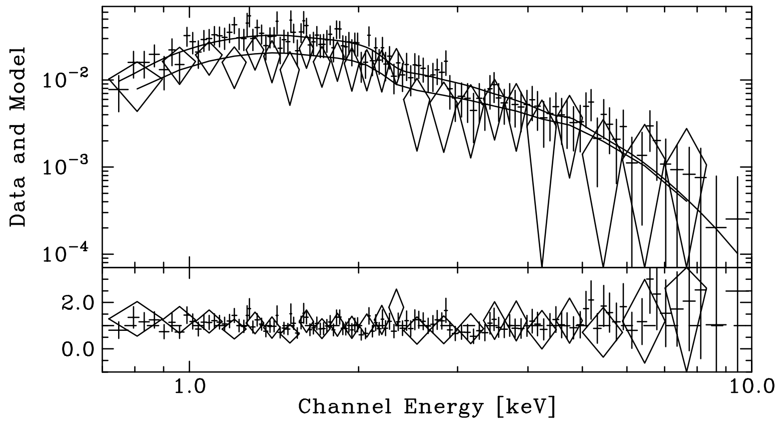


Fig. 4.— *ASCA* GIS spectra of MS 1603.6+2600 during orbital maximum (pluses) and minimum (diamonds). The top panel shows the data and the model (see text for details), while the bottom panel shows the data to model ratio.

### 3.3. Spectral analysis

Despite the improvement over the *ROSAT* PSPC spectrum, we have not been able to draw a definite conclusion from the average *ASCA* spectrum of MS 1603.6+2600. It can be fit with a power law, a bremsstrahlung, or a Comptonization model: discrimination among these continuum models proved impossible because high signal-to-noise ratio was not achieved over a sufficiently wide bandpass. No discrete features are obvious. Regardless of the continuum model, the 0.7–10 keV flux of MS 1603.6+2600 during the *ASCA* observation was $\sim 4.0 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ ($\sim 4.8 \times 10^{34}$ [d/10 kpc]$^2$ ergs s$^{-1}$). Ignoring the difference in spectral shapes, the $\sim$8 fold increase in count rate at the peak of the burst implies a peak luminosity of $\sim 3.8 \times 10^{35}$ [d/10 kpc]$^2$ ergs s$^{-1}$).

The average *ASCA* flux value indicates a significant long-term variability in MS 1603.6+2600. The *Einstein* IPC 0.3-3.5 keV flux of 1.14 $\times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ (Morris et al 1990) is roughly a factor of 4 lower than the *ASCA* value, although both the bandpass and the assumed spectral shape are different. Back prediction of *Einstein* count rate based on *ASCA* flux and the best-fit bremsstrahlung model also points to a factor of $\sim$4 change in flux. Similarly, MS 1603.6+2600 appears to have been fainter by a factor of $\sim$7 during the *ROSAT* observation, compared to 1997 August.

We also compared the spectrum during the orbital minimum to that of the maximum, by simultaneously fitting the two using the same bremsstrahlung model (identical kT and normalization). For the maximum, we assumed no absorption, since the interstellar column, of the order of $10^{20}$ cm$^{-2}$ according to the *ROSAT* PSPC spectral fit (Hakala et al 1998), is too small to be detectable with *ASCA*. For the minimum spectrum, we have added an absorption component. Either a simple absorber of $N_H = 4.6 \times 10^{21}$ cm$^{-2}$ ($\chi^2$=70.6 for 140 PHA bins and 4 degrees of

freedom) or a partial covering absorber of $N_H = 1.3 \times 10^{23}$ cm$^{-2}$ and a covering fraction of 37% ($\chi^2$=64.8 for 140 PHA bins and 5 degrees of freedom) can be used to fit both spectra. The latter is shown for the GIS data in Figure 4.

## 4. Discussion: the Nature and the Location of MS 1603.6+2600

We have observed an orbital minimum in the *ASCA* light curve which is broad and partial. Our re-analysis of the *ROSAT* PSPC light curve shows that a similar minimum was present during the first half of the 1991 observation, but disappeared during the second half.

In the ADC model that we favored in our earlier report (Mukai et al 1999), this minimum is caused by a partial eclipse of an extended X-ray source, whose size is a significant fraction of the binary separation. An ADC source is an LMXB seen at a high inclination angle. The central X-ray emitting region is blocked from our direct view by the accretion disk. A fraction (1–10%) is scattered into our line of site by the ADC above the accretion disk. Although this interpretation has several attractive properties, MS 1603.6+2600 does not show the smooth, quasi-sinusoidal modulation which is seen in the prototype ADC source, X1822−372 (Hellier & Mason 1989). The orbital light curves of ADC sources generally appear to be stable from one cycle to the next, while the *ROSAT* data show MS 1603.6+2600 to be otherwise. In addition, the spectrum of X1822−372 is softer during the partial eclipse, which is the reverse of what we observe in MS 1603.6+2600. Therefore, the behavior of MS 1603.6+2600 differs in detail from those of well-established ADC sources such as X1822−372. Moreover, the ingress into the orbital minimum in MS 1603.6+2600 (Figure 2) takes place in less than one phase bin (1/32th of the orbital cycle). It is difficult to construct a geometry of an extended X-ray source that leads to a broad, partial eclipse yet with such a relatively rapid ingress.

On the other hand, the behavior of MS 1603.6+2600 is similar to that of dipping LMXBs such as XB 1916−053 (Homer et al 2001). In dippers, we believe that the central X-ray source (the accretion disk, the neutron star, or both) is occulted by azimuthal structure of the accretion disk. The preferential location of the structure in binary frame defines the envelope of phases during which dips occur. The dip durations and depth change from epoch to epoch, sometimes within a single observation. Spectrally, dips are deeper at low energies, although simple absorption models often do not fit the data, instead requiring a partial covering absorber. In all these respects, the *ASCA* data of MS 1603.6+2600 are consistent with the dipper interpretation. We therefore favor this interpretation over the ADC model.

As a dipper, MS 1603.6+2600 must possess an accretion disk. This immediately excludes the AM Her-type magnetic CVs (in which the magnetic field is so strong as to prevent the formation of a disk) from consideration. It is still possible that MS 1603.6+2600 is a dipping CV with an accretion disk. For example, U Gem, the prototype dwarf nova, is a dipper (Szkody et al 1996). However, all the objections raised to date remain valid, most notably that the $f_X/f_{opt}$ ratio is too high: U

Gem is $\sim$1,000 times brighter than MS 1603.6+2600 in the optical while only $\sim$4 times brighter in the *ASCA* band. Magnetic CVs of the intermediate polar type, which has partial accretion disk, also show X-ray dips (Hellier et al 1993). However, their defining characteristic is a strong spin modulation in the X-rays, which we do not see. Thus, if MS 1603.6+2600 is a CV, it must be an unusual example.

Moreover, a burst-like event like the one we have seen in MS 1603.6+2600 has never been reported in any X-ray observations of CVs. We therefore assume, as a working hypothesis, that MS 1603.6+2600 is an LMXB containing a neutron star and the burst is a Type I event. This suggest MS 1603.6+2600 is at a great distance, since the typical persistent luminosity of a dipper is a few times $10^{36}$ $\mathrm{ergs\,s^{-1}}$ and the typical burst peak luminosity is a few times $10^{37}$ $\mathrm{ergs\,s^{-1}}$. Given the observed flux values, this would require $d \gg 10$ kpc.

Is this a serious weakness of this model? Is there anything in the Galactic halo out to, say, $d \sim$50 kpc? To answer these questions, we have conducted a simple search for globular clusters near the direction of MS 1603.6+2600. The nearest match was found to be Palomar 14 (Sarajedini 1997), $\sim 11^\circ$ away on the sky at an estimated heliocentric distance of 73.8 kpc.

This suggests possible, though speculative, scenarios as to how MS 1603.6+2600 might have formed in the outer halo. First, it may have formed in Palomar 14 itself and escaped. Of the $\sim$150 Galactic globular clusters, 12 harbor a luminous X-ray binary (Deutsch et al 2000). The same stellar encounters that form these LMXBs eject a significant number of resultant binaries. One calculation (Portegies Zwart et al 1997) suggest the fraction of the escaped binaries may be about a third of those that have survived in the globular cluster, thus we expect several "non-globular-cluster" LMXBs to have escaped from the parent cluster. Similar escapees from a cluster much closer to the Galactic center would have been assimilated into the Galactic bulge, and its origin would have become obscured. If MS 1603.6+2600 was ejected from Palomar 14 at a velocity of 10 $\mathrm{km\,s^{-1}}$, it would have taken it $\sim$1 Gyr to move 10 kpc, which is the minimum distance implied by the current angular separation of $11^\circ$. Thus it appears possible to have a reasonable combination of space velocity and lifetime of MS 1603.6+2600 to explain its current location, for an assumed origin in Palomar 14.

Another speculative scenario is related to the possible origin of Palomar 14, and many other outer halo globular clusters, in dwarf elliptical satellites of the Milky Way (van den Bergh 2000). Several outer halo clusters are associated with the Sagittarius dwarf. Similarly, Palomar 14 may be associated with an undiscovered extant satellite, or one that has been tidally disrupted. In either case, MS 1603.6+2600 could be a member of this hypothetical satellite galaxy.

If we assume a physical association between MS 1603.6+2600 and Palomar 14, at a distance of $d \sim 70$ kpc, then the average luminosity during *ASCA* observation was $\sim 2.4 \times 10^{36}$ $\mathrm{ergs\,s^{-1}}$ and the peak burst luminosity was $\sim 1.9 \times 10^{37}$ $\mathrm{ergs\,s^{-1}}$, both of which are normal for a bursting, dipping LMXB, although still with an unusually low $f_X/f_{opt}$ ratio. Evolutionary scenario Ia of Ergma & Vilhu (1993), similar to short period CVs, predicts a similar luminosity and bursting behavior, and

hence fits our outer halo interpretation. However, this may be a coincidence if MS 1603.6+2600 is indeed formed in Palomar 14, since globular cluster LMXBs form in a distinct manner from field LMXBs.

If our interpretation is correct, MS 1603.6+2600 is a close analog of XB 1916−053, including the strong variabilities of the dip morphology. In fact, the second optical period obtained via Fourier transform (Vilhu et al 1993) may be real, indicating that MS 1603.6+2600 is a permanent superhumper (Haswell et al 2001), another characteristic of XB 1916−053. If so, it would be possible to estimate the mass ratio of MS 1603.6+2600 using the fractional period excess.

## 5. Summary and Future Prospects

We have presented our *ASCA* observation of the unusual high-latitude X-ray binary, MS 1603.6+2600. We have detected a burst and an orbital modulation consistent with a dipping behavior, and presented an outer halo LMXB model as perhaps the least contrived interpretation.

Future X-ray observations can test our interpretation. In particular, the detection of other bursts with better sensitivity is necessary to confirm the Type I interpretation spectroscopically. Moreover, if we are lucky enough to catch a radius expansion burst, a reliable distance and other parameters can be derived. The ingress and egress to the orbital minimum should be investigated further, so that we can can conclusively choose between the dipper and the ADC interpretations. At the same time, further optical observations should clear up the issue of possible multiple periodicities.

Pending such observations, we tentatively conclude that MS 1603.6+2600 may be the most distant Galactic X-ray binary known. Moreover, this may be an escaped globular cluster LMXB, something we cannot confidently observe near the Galactic center, or may be a relic of the hierarchical formation of the Milky Way halo.

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